Comparison of the vertical compliance and rotational stiffness of natural, hybrid and artificial football surfaces

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ORIGINAL PAPER

Comparison of the vertical compliance and rotational stiffness of natural, hybrid and artificial football surfaces

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Abstract

The playing surface in football plays a pivotal role in player performance, safety, and overall game quality. With evolving regulations and continuous technological advances in football surfaces (natural, hybrid, and artificial turf), understanding their performance characteristics is essential. This study evaluated the vertical compliance and rotational stiffness of football surfaces using two test devices adopted by the FIFA Quality Programme: the Advanced Artificial Athlete and the Rotational Traction Athlete. Measurements were taken from 126 football pitches and turf samples, assessed in-situ and in the laboratory, respectively, which encompassed various natural, hybrid, and artificial turf systems. Results indicated significant differences in vertical compliance, with artificial turfs exhibiting higher peak shock absorption, greater peak deformation, and increased energy return compared to natural and hybrid turfs, suggesting that artificial turfs are more compressible and more elastic. Rotational stiffness measurements revealed that while peak torque values were similar across most surface types, natural and hybrid turfs demonstrated significantly higher resistive torque at 10 degrees of rotation than artificial systems. The findings of this study informed revisions of the performance thresholds adopted within the FIFA Quality Programme, which specify the global quality requirements for football playing surfaces.

1 Introduction

The playing surface is a critical element of football, influencing player performance, safety, and overall game quality. Over the years, football surfaces have evolved into three principal categories of turf; natural turf, hybrid turf and artificial turf. Within each turf category, the surfaces exhibit a range of performance characteristic that affect player biomechanics and game dynamics [1–3]. For example, natural turf football surfaces have been shown to be stiffer than artificial turf surfaces, while peak vertical accelerations have been shown to be higher while running on artificial surfaces [1]. Numerous researchers have attempted to summarise the range of mechanical performance characteristics within each turf category; however, it is not clear if the measurements presented in previous studies are fully representative of the modern game. Principally, previous studies have often relied on a relatively small sample size of different pitches within a small geographical region. For example, two of the largest of these previous studies by Thanheiser et al. [4] and Nunome et al. [5] collected in-field from eight natural and hybrid football pitches in Germany, and nine natural, hybrid and artificial football pitches in Japan, respectively. Playing surfaces are continuously evolving with new technologies and maintenance strategies, and some of the historical benchmark data is now more than a decade old [1, 4–8].

The amended Advanced Artificial Athlete (AAA), is an evolution of the standard artificial athlete described in both EN 14808:2005 [9] and BS EN 14809:2005 [10]. The AAA is used to assess the mechanical behaviour of sports surfaces, including peak shock absorption, peak deformation and energy returned. Following previous studies which have validated the AAA [11, 12], as well as inter-laboratory proficiency testing, it is now recognised by several international sports federations as a reference device for football surface

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testing of surface 'hardness'. The Rotational Traction Athlete (RTA) was created as a successor to the original EN 15301–1 rotational resistance device [13] and was designed to measure rotational traction and shear stiffness on both synthetic turf and natural grass fields [14], for surface 'grip'. These enhanced test devices were developed to provide more detailed information on turf characteristics that align more closely to the player experience on artificial turf and helps to identify whether athletes are at risk from too hard/soft surfaces or from slipping or injury due to excessive traction [15]. The amended AAA adds the capability to measure energy restitution (energy return), in addition to shock absorption and vertical deformation measures provided by the previous Artificial Athlete (AA) device, providing a more comprehensive assessment of a sports surface's performance in regard compliance under vertical load.

Artificial turf has become increasingly popular as a high usage year-round substitute for natural grass. Artificial turf generally comprises the following components: a lower base layer made from gravel or stone; an artificial grass carpet, including a backing material and artificial grass fibres; and one or more infill materials. In addition, many artificial turf systems include a shock pad layer below the carpet of varying thickness and density to provide additional cushioning and performance characteristics. A schematic showing the component layers of an artificial turf system is shown in Online Resource 1.1. The infill material is used to help hold the grass fibres upright and provide cushioning and boot stud engagement, as well as ensuring drainage. Infill is the portion of the artificial turf that mimics the role of soil in a natural grass system. Historically, infill options were limited to sand and styrene-butadiene rubber (SBR) rubber crumb (from end-of-life tyres, ELT). However, new infill materials have been introduced in recent years alongside a move to denser carpets and non-infill systems [15, 16]. The main types of current artificial turf infill materials can be broken down as follows:

- End-of-life tire (ELT) infill—commonly known as SBR rubber crumb.
- Vegetal infill – natural/organic materials e.g. cork, wood, coconut, olive pits.
- Mineral stabilized infill – inorganic infill made from non-living, mineral-based materials e.g. sand.

Each of these infill materials has its own unique qualities and characteristics which make it suitable for different applications. Natural turf is grown and maintained specifically for use on sports fields. It consists of a combination of grasses that are chosen for durability, wear resistance, and an ability to recover quickly from damage. A natural turf sports surface consists of a turf surface and a turf base layer. In addition, it is also recommended to install a drainage system, such as pipeless drainage slots or a drainage layer. Hybrid turf sports surfaces combine natural grass with artificial fibres, typically polyethylene, stitched deep into the rootzone to provide the feel and look of natural grass with enhanced durability and stability. Hybrid turf systems can be categorised in terms of their construction into either stitched or carpet hybrid systems. A stitched hybrid turf system involves injecting polyethylene fibres into the rootzone of a natural grass playing surface, resulting in a hybrid pitch that combines the best qualities of natural and synthetic turf capable of withstanding intensive use. A carpet hybrid turf system is a reinforced playing surface made from weaving polyethylene fibres into a backing to create a carpet. This carpet is then filled with a special rootzone where natural grass seeds are planted, with roots then growing through the carpet and intertwining with the artificial fibres. These systems can be installed as pre-grown carpet mats, allowing for instant play, or as a system where natural grass is grown on-site after the synthetic carpet is laid.

The purpose of the FIFA Quality Programme (FIFA QP) is to endorse football surface products that meet strict quality requirements to improve the game and safeguard players, clubs and associations. If a football pitch satisfies the three required steps within the FIFA QP, including laboratory testing, installation and field testing, FIFA will grant the facility either FIFA Quality or FIFA Quality Pro certification. FIFA Quality certification is for recreational, training and grassroots football, typically accommodating 40–60 h of play per week. FIFA Quality Pro certification is reserved for pitches that satisfy higher standards of performance and safety required for professional football. This requires a more rigorous testing protocol, maintenance practices as well as compliance with international match standards. However, the existing standards were originally established using measurements gathered in 2001, which may not represent the global range of surface technologies now in use. With substantial advances in natural, hybrid, and artificial turf systems, a re-evaluation of the performance characteristics in each turf category is required. This study measured the performance characteristics using the AAA and RTA test devices across a broad spectrum of current surface types, with the objective of generating the evidence base necessary to redefine performance thresholds within the FIFA QP [17]. The resulting measurements will provide a foundation for updated performance thresholds within global football surface quality standards.

2 Methods

Two mechanical test devices were used to collect data on the performance characteristics of a large sample of natural turf, hybrid turf and artificial turf football surfaces. In total, data were collected on 126 different football pitches and turf samples.

2.1 Advanced artificial athlete

The AAA, presented in Fig. 1, is used to assess the vertical impact behaviour of the playing surface [13]. The test protocol used in this study corresponds to the 2024 FIFA Test Manual [13], with measurements obtained across all sites and laboratories collected according to this updated protocol. The test procedure states that a calibrated falling mass with an attached spring (2 kN/mm ± 100 N/mm), accelerometer and steel test foot are dropped onto the surface from a height of 60 mm. Acceleration is recorded from release to the end of impact. The total mass of the accelerometer, spring, test foot and falling mass must be 20 kg ± 100 g. From the embedded accelerometer, the following performance characteristics of the surface are calculated from a single drop according to the updated 2024 FIFA test method [13]:

1. Peak shock absorption (%) (in relation to a rigid surface) – measures the extent to which the football surface reduces peak force in comparison to a fully rigid surface.
2. Peak deformation (mm)—describes the maximum deformation of the surface during the impact event.
3. Energy return (J)—measures the magnitude of energy returned to the device's test foot post-impact, with example curves of test specimen force versus deformation shown in Online Resource 1.2.

2.2 Rotational traction athlete

The RTA is used to assess the rotational resistance of the playing surface [13] (Fig. 2). The device applies a known normal load of 450 N to the surface via a circular test foot with six studs. The test foot is rotated through the surface at a prescribed angular velocity of 30 degrees/second, and the resistive torque is measured in relation to angle and time. This allows the following performance characteristics of the surface to be calculated:

1. Peak torque (Nm)—measures the maximum resistive torque that the football surface exerts on the rotating test foot. An example plot of torque versus angle from a measurement trial using the RTA is shown in Online Resource 1.3.
2. Shear stiffness (Nm/degrees)—measures the rotational shear stiffness that the football surface exerts on the rotating test foot.
3. Torque at 10 degrees rotation (Nm)—measures the resistive torque exerted by the playing surface at 10 degrees of rotation.

2.3 Pitch tests

Pitch tests were conducted by Labosport, a FIFA accredited test institute, using FIFA accredited technicians. Tests

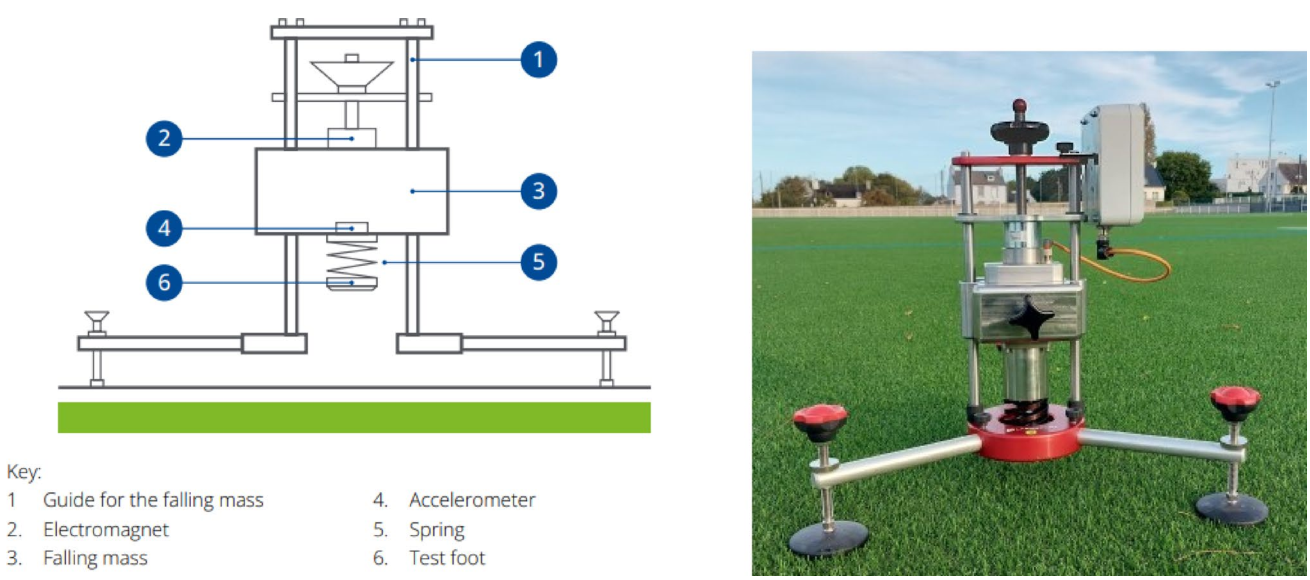

Fig. 1 The Advanced Artificial Athlete (AAA) [13]. **a** Left image shows a schematic of the AAA test apparatus; **b** Right image shows the AAA test apparatus in use in the field

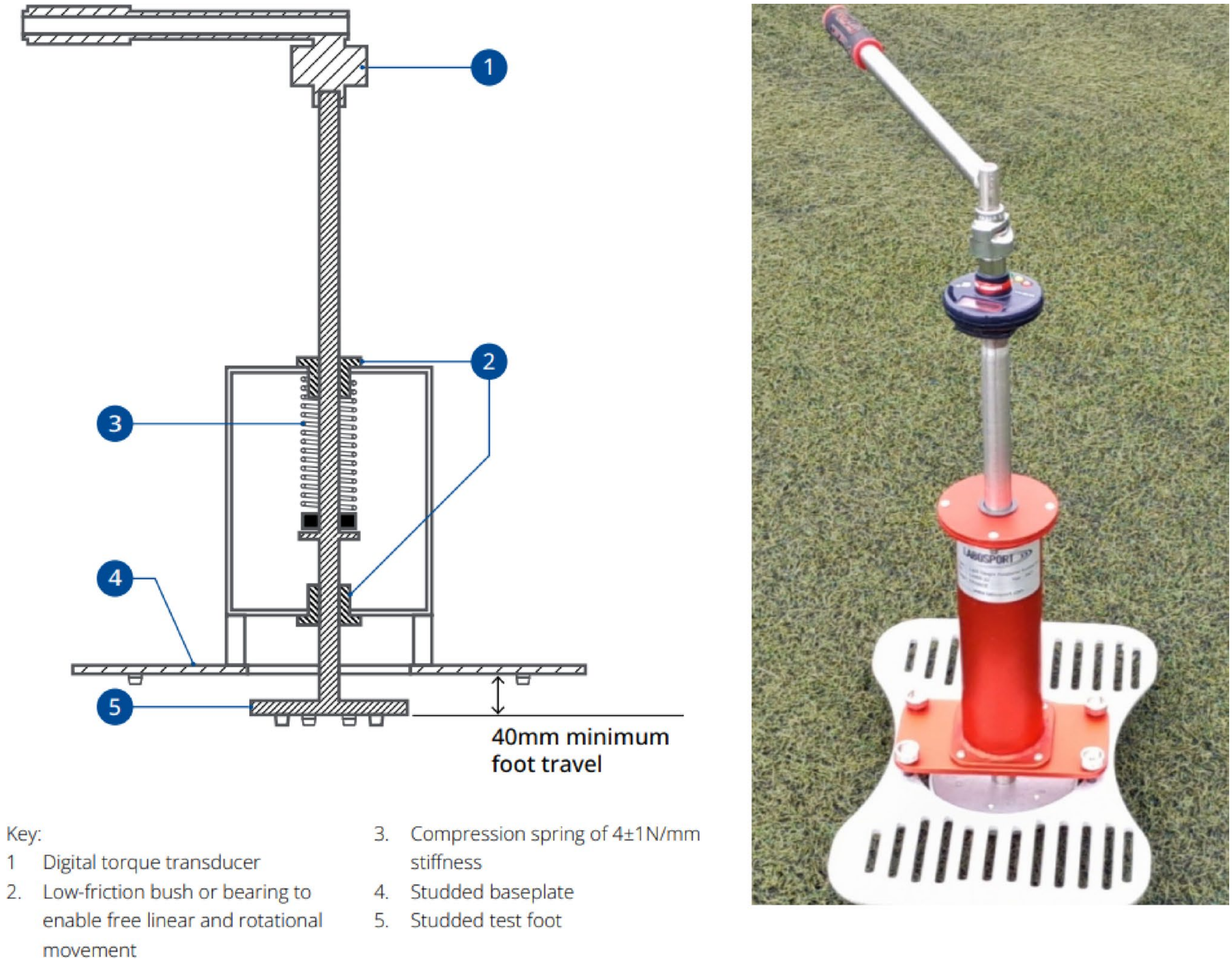

Fig. 2 The Rotational Traction Athlete (RTA) [13]; **a** Left image shows a schematic of the RTA; **b** Right image shows the RTA in use in the field

were conducted at all pitch test locations, as described by the FIFA Quality Programme for Football Turf [17] (Fig. 3). Nineteen different test locations were used to determine the vertical compliance of a pitch using the AAA, and six different test locations were used to determine the peak torque and rotational shear stiffness of a pitch using the RTA. The same pitch locations were tested across all turf categories in this study where applicable, with the mean value of each measured mechanical characteristic across all measured locations used to describe a pitch in the subsequent analyses.

The data collection on 126 different football pitches and turf samples took place over two football seasons between 2022 and 2023. The specific names and test dates of each pitch location cannot be provided, as this would breach client confidentiality. The research study sought to gather data on as wide a range of surface types as possible within each turf category (natural, hybrid and artificial). Furthermore, the study sought to include data from different international regions, and at different periods within the playing season (summer/winter), to help develop a greater understanding of the variability in natural pitch conditions.

The data collection on natural turf pitches was conducted on professionally maintained surfaces with drainage design. These pitches were primarily located in France and in the UK and were either the stadium pitch, or a training ground for a professional football club. The data collection on hybrid turf pitches was conducted on elite surfaces and included stitched hybrid systems and carpet hybrid systems. The pitches included stadium surfaces from the FIFA World Cup Qatar 2022, the English Premier League, France's Ligue 1 and other elite venues. The data collection on artificial turf pitches was conducted on FIFA compliant venues in the UK and in the Netherlands. All artificial pitches were between 2 and 4 years old and included systems both with and without a shock pad layer. Additional data was collected on artificial turf systems in controlled laboratory conditions and included systems with a variety of vegetal infills, mineral only infills, and non-infill systems.

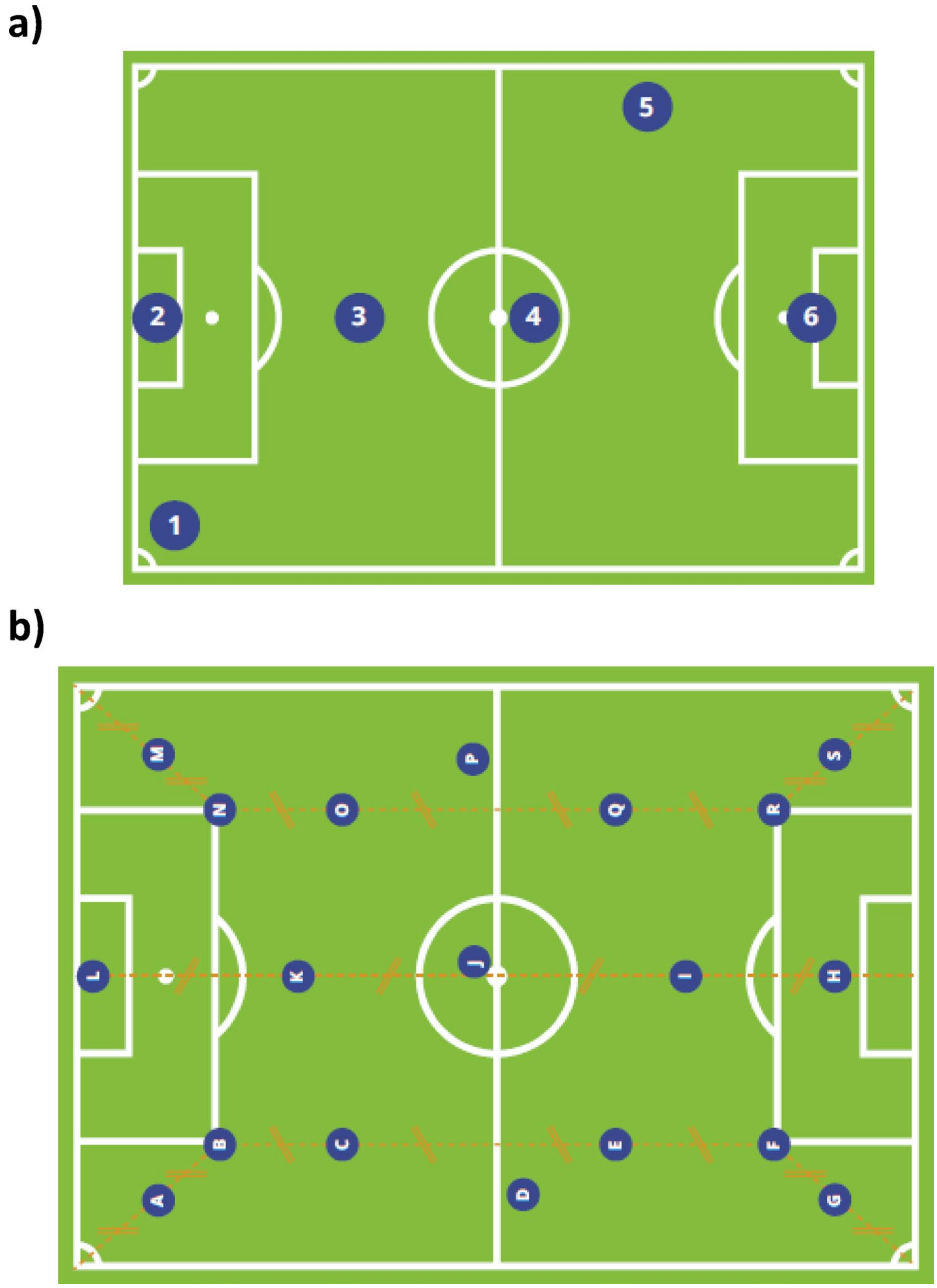

Fig. 3 **a** Field test positions where all on-site tests must be conducted under the FIFA Quality Programme for Football Turf including measures of peak torque and rotational shear stiffness using the RTA, **b** Pitch test locations for determining peak shock absorption using the AAA [13]

Laboratory samples were prepared in accordance with the BS EN 12229:2014 standard for the preparation of synthetic turf and needle-punch test pieces [18]. This procedure includes adding infill materials according to the manufacturer's instructions, consolidating the infill material using a conditioning roller for 50 cycles and then brushing the surface of the carpet in two perpendicular directions using a stiff brush to lift the pile before testing. It is acknowledged that despite conditioning of the turf samples used in laboratory testing, the data would not be perfectly comparable with the in-field data collected from installed pitches. A summary of the pitches and turf samples assessed in this study are presented in Table 1.

2.4 Statistical analysis

To compare the performance characteristics between the six turf categories, a one-way ANOVA was conducted, with P values < 0.05 considered statistically significant. The test was used to determine if there were statistically significant differences in the means of the six categories. Data was first checked for normality using the Shapiro–Wilk test and

Table 1 Summary of the six different turf categories evaluated in the study

Turf category	Description	Location	Playing level	No. of pitches / systems
Natural Turf (NT)	Professional maintenance and drainage design	England France	Premier League / National League Ligue 1	26
Hybrid Turf (HT)	Stitched hybrid and carpet hybrid	England France Qatar	Premier League Ligue 1 FIFA World Cup	46
Artificial Turf with ELT* infill (AT ELT)	Artificial Football Turf for FIFA QP-Compliant Systems with SBR ELT infill (half with a shock pad, half without)	England Netherlands	National League Eredivisie	18
Artificial Turf with Vegetal infill (AT Veg)	Artificial Football Turf for FIFA QP-Compliant Systems with vegetal infill and shock pad	Laboratory based	–	13
Mineral Stabilized Artificial Turf (MF)	Turf system partly filled with mineral infill that does not exceed 25% of the non-elongated pile height with shock pad	Laboratory based	–	9
Non-Filled Artificial Turf (NF)	Turf system without any infill but with shock pad	Laboratory based	–	14

*ELT, end-of-life tires

homogeneity of variances using Levene's test. If assumptions of homogeneity were met, a one-way ANOVA was performed, with post hoc pairwise comparisons conducted using Bonferroni adjusted significance values for multiple comparisons to identify which of the turf categories were significantly different. In cases where the homogeneity assumption was violated and sample sizes were considerably different, analysis of differences between surfaces was conducted using a one-way ANOVA with the Welch statistic and Games-Howell post hoc tests. Effect size (Eta squared (η^2)) was calculated to quantify the proportion of variance in the measured performance characteristics that is explained by the different turf categories. The following thresholds were used to interpret the size of measured effects: small ($\eta^2=0.01$), medium ($\eta^2=0.06$) and large ($\eta^2=0.14$) [19]. All statistical analyses were performed using SPSS software (version 31.0, IBM, USA).

3 Results

Levene's test of homogeneity of variance showed that the variances for peak shock absorption ($F(5,310)=3.10$, $p=0.01$), energy return ($F(5,306)=4.87$, $p<0.001$) and shear stiffness ($F(5, 33)=3.14$, $p=0.02$) were not equal. As a result, differences between surfaces for these variables were assessed using the Welch statistic and Games-Howell post hoc tests.

3.1 AAA

Peak shock absorption values were typically lower for hybrid turf and natural turf than the artificial turf categories, and of the pitches measured 68% were within the required range for FIFA Quality Pro and FIFA Quality certification (Fig. 4). The results showed a statistically significant difference in peak shock absorption between the turf categories, $F(5, 30.58)=40.25$, $p<0.001$. Post hoc analysis with Games-Howell revealed significant differences between natural turf and hybrid turf ($p<0.001$), between natural turf and artificial turf with ELT infill ($p<0.001$), between natural turf and non-filled artificial turf ($p<0.001$), as well as between hybrid turf and artificial turf with ELT infill ($p<0.001$) and between hybrid turf and non-filled artificial turf ($p<0.001$). The effect size (eta squared, η^2) was 0.220, suggesting a large effect of football surface type on peak shock absorption. In summary, hybrid turf and natural turf displayed the lowest values for peak shock absorption, while the artificial turf systems exhibited higher shock absorption, with non-filled artificial turf having the highest shock absorption.

Peak deformation was typically lower for hybrid turf and natural turf than the artificial turf categories. Of the products measured, 85% were within the required range for FIFA Quality Pro certification, while all but a small number of samples (2%) met the FIFA Quality certification threshold (Fig. 5a). The results showed a statistically significant difference in peak deformation between the turf categories, $F(5, 311)=46.27$, $p<0.001$. Post hoc analysis with a Bonferroni adjustment revealed statistically significant differences between natural turf and all other surfaces ($p<0.005$), as well as between hybrid turf and all other surfaces ($p<0.001$). The effect size (eta squared, η^2) was 0.427,

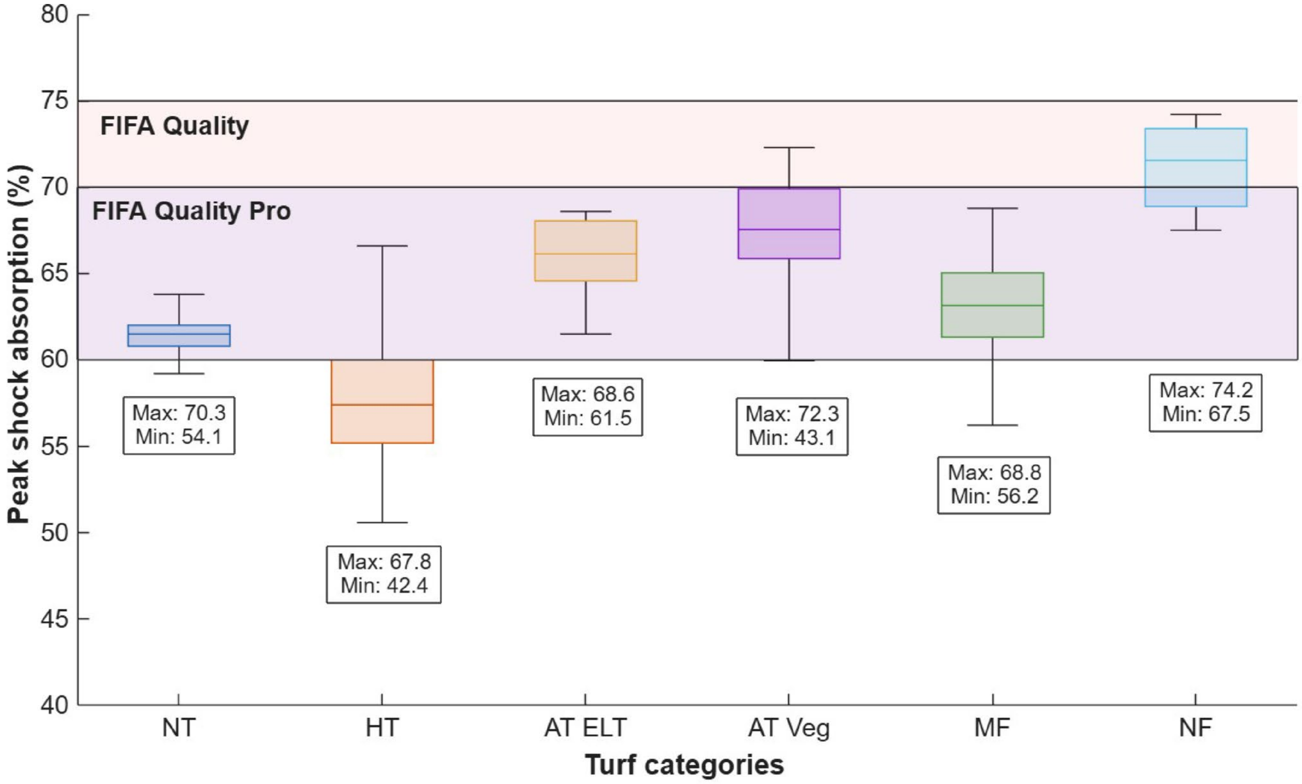

Fig. 4 Box plots of peak shock absorption for the different turf categories. The max and min values for each turf category, as well as the required peak shock absorption ranges for FIFA Quality Pro and FIFA Quality certification are shown

suggesting a large effect of football surface type on peak deformation. The hybrid and natural turf pitches displayed a steeper force–displacement curve than the artificial turf categories, indicating their increased stiffness (Fig. 5b). Hybrid turf in turn reached the highest peak force indicating that it can withstand higher loads whilst deforming the least. Conversely, non-filled artificial turf displayed a much shallower force–displacement curve, indicating its reduced stiffness.

Energy return was typically lower for hybrid turf and natural turf than the artificial turf categories (Fig. 6). The results showed a statistically significant difference in energy return between the turf categories, $F(5, 28.80) = 198.67$, $p < 0.001$. Post hoc analysis with Games-Howell revealed significant differences between natural turf and all other surfaces ($p < 0.001$), as well as between hybrid turf and all other surfaces ($p < 0.001$). The effect size (eta squared, η^2) was 0.849, suggesting a large effect of football surface type on energy return.

3.2 RTA

Peak torque was typically lower for mineral stabilised artificial turf systems and non-filled artificial turf categories. Of the pitches measured, 79% were within the required range for FIFA Quality Pro certification, while an additional 12% were within the required range for FIFA Quality certification (Fig. 7a). The results showed a statistically significant difference in peak torque between the turf categories, $F(5, 64) = 19.54$, $p < 0.001$. Post hoc analysis with a Bonferroni adjustment revealed statistically significant differences between mineral stabilized artificial turf systems and all other surfaces ($p < 0.001$), as well as between non-filled artificial turf and all other surfaces ($p < 0.001$). The effect size (eta squared, η^2) was 0.604, suggesting a large effect of football surface type on peak torque.

The mean torque measurement plots of hybrid, natural and artificial turfs measured using the RTA device in this study are displayed in Fig. 7b. Differences in the rotational stiffness characteristics can be observed between the different surface types, with peak torque broadly similar between natural, hybrid and artificial turfs, but lower in non-filled artificial systems.

Values for shear stiffness were lower for non-filled artificial turf categories (Fig. 8). The results showed a statistically significant difference in shear stiffness between the turf categories, $F(5, 12.04) = 14.66$, $p < 0.001$. Post hoc analysis with Games-Howell revealed statistically significant differences between non-filled artificial turf and all other surfaces ($p < 0.05$) except natural turf, as well as between hybrid turf and artificial turf with vegetal infill ($p < 0.05$). The effect

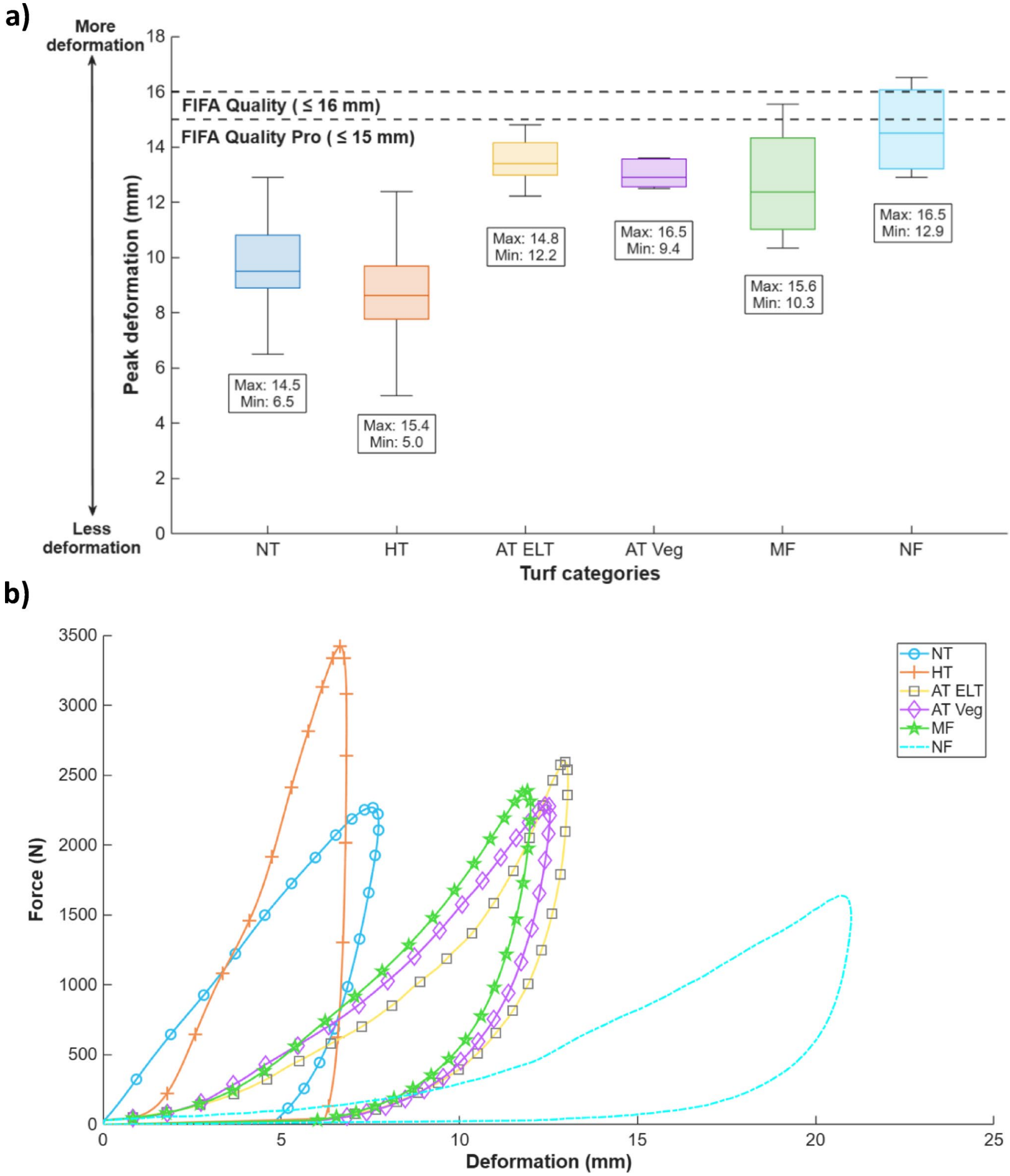

Fig. 5 **a** Box plots of peak deformation results for the different turf categories. The max and min values for each turf category, as well as the required peak deformation thresholds for FIFA Quality Pro and FIFA Quality certification are shown; **b** Comparison of force deflection behaviour of individual samples of the different turf categories tested in this study

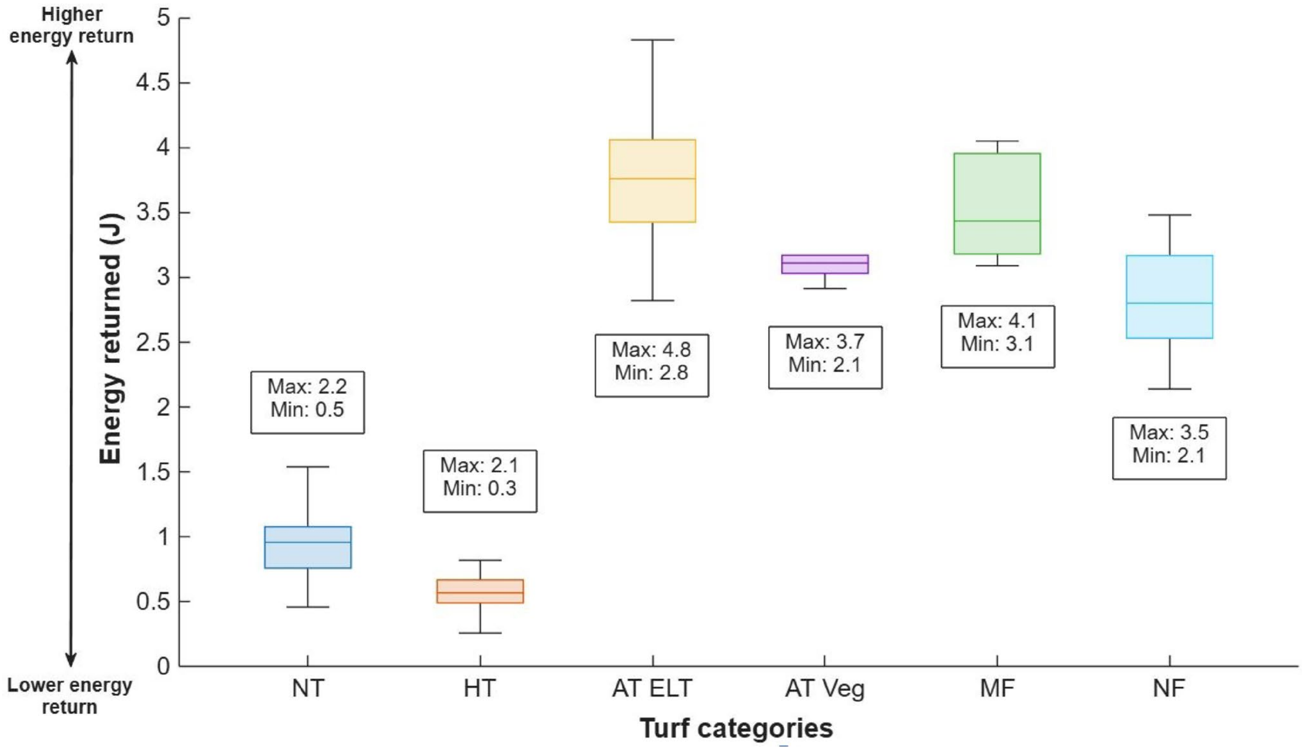

Fig. 6 Box plots of energy return results for the different turf categories. The max and min values for each turf category are shown

size (eta squared, η^2) was 0.551, suggesting a large effect of football surface type on shear stiffness.

Values for torque at 10 degrees were higher for natural and hybrid turf than for artificial turf categories (Fig. 9). The results showed a statistically significant difference in torque at 10 degrees between the turf categories, F(5, 335.902, $p<0.001$. Post hoc analysis with a Bonferroni adjustment revealed statistically significant differences between hybrid turf and all artificial turf categories ($p<0.05$), as well as between natural turf and non-filled artificial turf ($p<0.05$). The effect size (eta squared, η^2) was 0.472, suggesting a large effect of football surface type on torque at 10 degrees.

4 Discussion

This study evaluated the vertical compliance and rotational stiffness of a large sample of natural turf, hybrid turf and artificial turf football surfaces. This study is notable as it represents one of the largest datasets of football turf performance characteristics measured in accordance with FIFA Quality Programme protocols [13, 17], over a range of turf categories that are representative of those used in the modern game.

Previous studies have examined the performance characteristics from various types of natural, hybrid and artificial turfs used in football, as well as their impact on game dynamics [1–8]. However, these studies have typically been limited to relatively small samples of different pitches within a confined geographical region, as well as some of them having been conducted more than twenty-years ago. This is significant since football playing surfaces continue to evolve, driven by new technologies, maintenance strategies and regulations, such as recent restrictions on the intentional use of microplastics in products within the European Union [20]. In contrast, this study assessed the performance characteristics of 126 different football pitches and turf samples over a two-year period between 2022 and 2023, gathering information on a wide range of surface types within each turf category (natural, hybrid and artificial). Furthermore, the measurements taken in this study captures variations in existing natural pitch performance characteristics across different countries, different levels of football competition and at different times of the season, which had varying levels of effect on measured performance characteristics. For example, peak vertical deformation of natural pitches was considerably lower during winter than in summer, while in contrast, both energy return and shock absorption were higher during winter months compared to the summer.

When comparing pitches of the same surface type across geographical locations, different surface types displayed differing levels of variability. For example, when comparing hybrid pitches installed in England and in Qatar, there did not appear to be significant differences in their measured

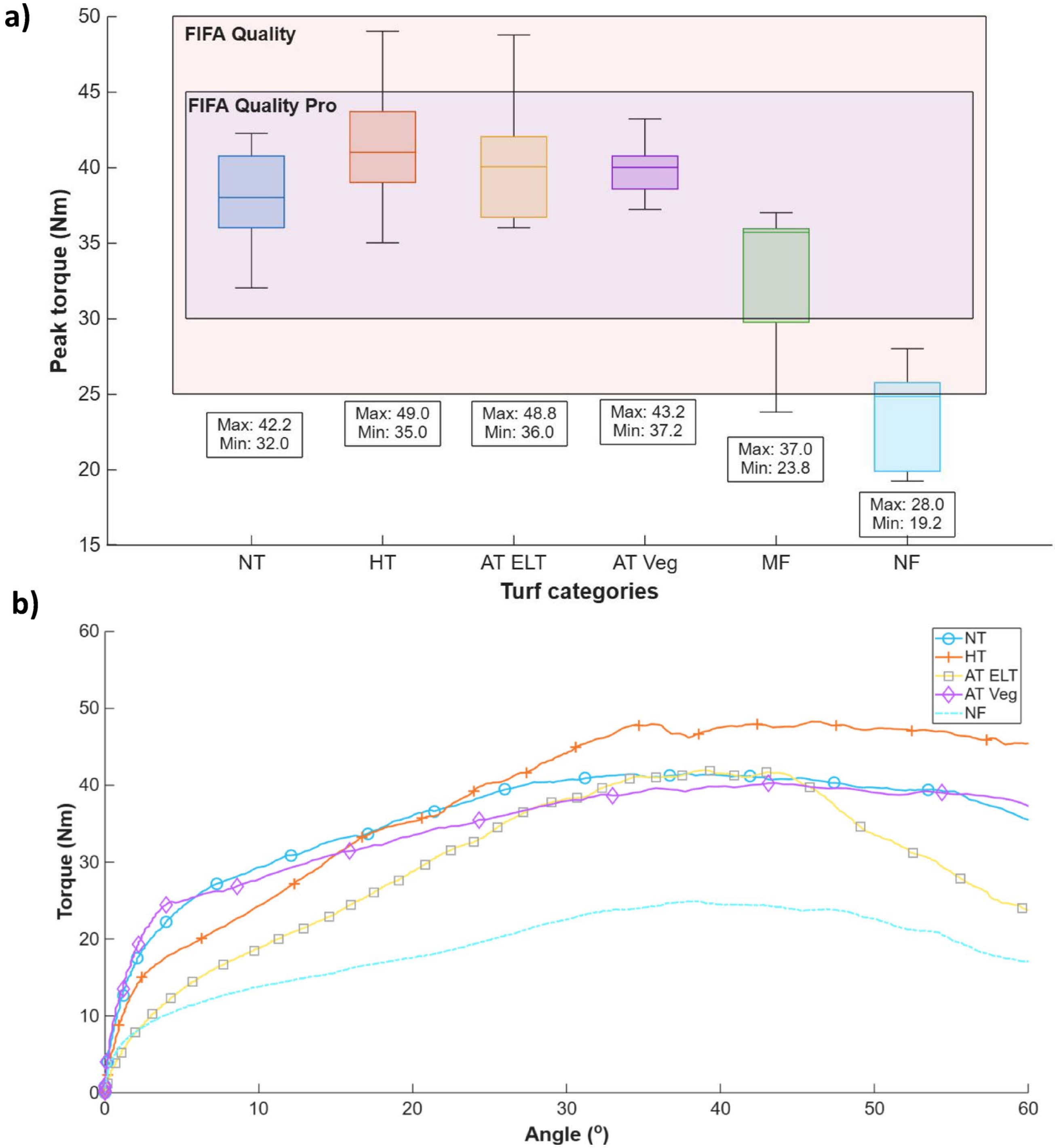

Fig. 7 **a** Box plots of peak torque results for the different turf categories. The max and min values for each turf category, as well as the required range of peak torque values for FIFA Quality Pro and FIFA Quality certification are shown; **b** Comparison of the torque behaviour of individual samples of the different turf categories tested in this study

characteristics. Conversely, when comparing artificial turf surfaces measured in England and the Netherlands, the pitches in the Netherlands displayed greater variability in peak shock absorption, deformation and energy return. However, these variations could be a result of different amounts of usage on those pitches. This would suggest that the performance characteristics of artificial surfaces are more consistent throughout the season than natural surfaces and less affected by where they are located.

This study found that well maintained natural and hybrid turf pitches that are used for elite level football have significantly different vertical compliance characteristics

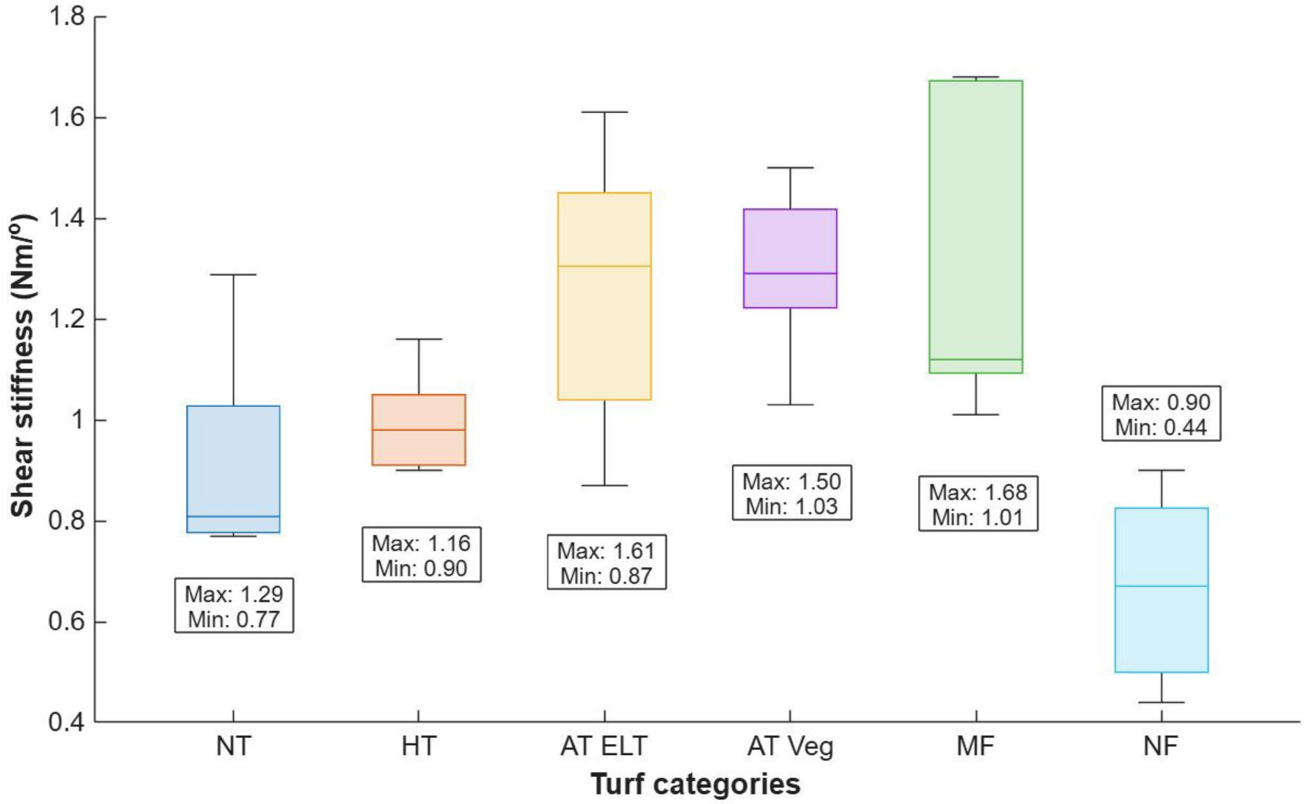

Fig. 8 Box plots of shear stiffness results for the different turf categories. The max and min values for each turf category are shown

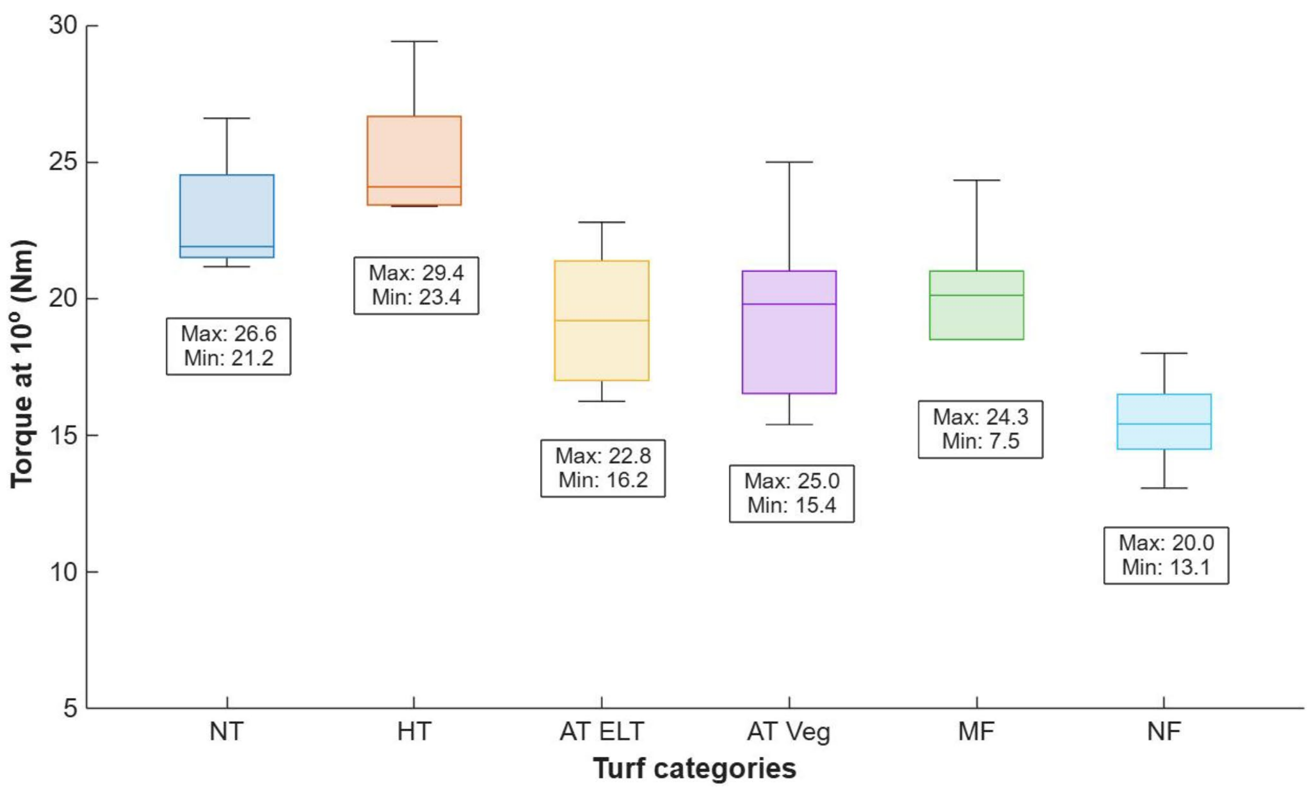

Fig. 9 Box plots of torque at 10° results for the different turf categories. The max and min values for each turf category are shown

compared to all artificial turf categories. Natural and hybrid turf pitches provide lower peak shock absorption, lower vertical deformation and lower energy return than artificial turf pitches, which agrees with the findings of previous studies [1, 8]. Consequently, natural and hybrid turf pitches can be characterised as having relatively high stiffness, low elasticity compared to artificial turf pitches, which can be characterised as having relatively low stiffness and high elasticity. In addition, it was observed in this study that natural turf provides more shock absorption than hybrid turf, which agrees with previous findings from Nunome et al. [5] and Thanheiser et al. [4]. This difference in peak shock absorption between natural and hybrid turf is largely due to differences in their material composition and structure. Though hybrid turf has improved durability and load bearing capacity compared to natural turf due to the synthetic fibres reinforcing the natural grass, this construction also reduces the extent to which hybrid turf can deform under loading and therefore its ability to reduce impact forces transmitted back to players.

The various artificial turf systems tested within this study were all designed to have vertical compliance in accordance with the FIFA 2015 Quality Pro requirements for artificial turf. For example, when adapting to the 2024 Test Methods, peak shock absorption values between 60 and 70% and peak deformation lower than 15 mm. However, these artificial turf requirements do not align with the new measurements on natural and hybrid turf [13, 17, 21]. These characteristics of the different surfaces are further exemplified when comparing the typical measured force deflection behaviour of hybrid, natural and artificial turfs. Natural and hybrid turf pitches produced steeper force–displacement curves compared to the artificial turf systems, indicating their increased stiffness. Hybrid turf surfaces recorded the lowest mean peak deformation values in response to the highest applied vertical force, resulting in the highest mean stiffness (k=513 N/mm), when compared to the other turf categories. For example, natural turf, artificial turf with ELT infill and non-filled artificial turf produced mean stiffness values of k=301 N/mm, k=201 N/mm and k=79 N/mm, respectively. In addition, it was observed that artificial turf systems display non-linear, behaviour whereby they produce high energy return at high deformation, which leads to players perceiving them as 'springy' but often bouncing back at the players at the wrong time.

In addition, this study revealed differences in the rotational stiffness characteristics between the different surface types. Peak torque was found to be broadly similar between natural, hybrid and artificial turf for FIFA QP-compliant surfaces, as seen in previous studies [6], but lower with mineral stabilized artificial turf systems and non-filled artificial systems. Conversely, torque at 10 degrees was found to be significantly higher for natural and hybrid turf compared to all artificial turf categories. This finding is in accordance with the early work of Fujikake et al. [8] and is notable in that it demonstrates that different surfaces can report similar values for peak torque, but different values for torque at 10 degrees. Previous research has shown that peak torque rotational traction results differ significantly from cutting and turning movements performed by athletes in the field [22–24]. Highspeed video footage of football players performing a "stop-and-turn" or cutting manoeuvre has demonstrated that players perform most of the rotation of their foot in the air before their foot is planted on the surface. While in contact with the surface, a player's foot typically only rotates around 12° in the turning direction [24]. As shown in the data collected in this study, torque continues to increase with increasing rotation angle, with peak torque values observed between 40° and 50° of rotation, far beyond what would occur in real world play scenarios. The new measurement, torque at 10 degrees, introduced by the Rotational Traction Athlete, reveals hitherto hidden differences in mechanical torque behaviour of turf systems and is more comparable to movements performed by players during play.

In addition, differences were observed between the turf categories, with non-filled artificial turf displaying the lowest shear stiffness values. A potential reason for these differences in shear stiffness seen between the non-filled turf and the other turf categories could be that the non-filled turf samples tested in the laboratory required further conditioning to make them more comparable to the installed pitch surfaces tested in this study. However, despite additional conditioning of the non-filled turf samples, the rollers used in conditioning applies standardised, repetitive stresses to the surface. In contrast, the in-service wear of installed football surfaces involves random, high-intensity, multi-directional, and non-uniform loading from players, including cutting movements and accelerations. As a result, the non-filled turf samples measured in the laboratory were likely less compacted and worn than the installed pitches and therefore produced lower shear stiffness values.

A further limitation of this study was the fact that turf samples tested in the laboratory could be considered as being 'fresh' or unused, excluding the conditioning process carried out when preparing the sample for testing, while the pitches tested in this study could have been in-service for 2–4 years or more. Previous studies have shown that turf samples measured in the laboratory are generally softer than artificial turf pitch surfaces, which have reduced compliance due to the effects of use over the course of a season and environmental factors [25]. As a result, this may have contributed to some of the measured differences between the turf categories assessed in this study depending on whether they were assessed in the laboratory or in the field. However, due to the significance of the differences in performance characteristics between turf categories identified in this study, it can be assumed the reduction in compliance only contributed to some of the measured differences. Nevertheless, future studies should attempt to further measures of these performance characteristics from turf samples which have undergone the same amount of wear.

The measurements obtained through this study informed recent updates to the performance thresholds for vertical compliance and rotational stiffness adopted within the 2024 FIFA Quality Programme for Football Turf, which specify the quality requirements for football playing surfaces globally. Given that previous thresholds were more than two decades old and derived from a single geographic region, a comprehensive assessment was essential to ensure that standards for football surface quality reflect contemporary technologies and playing conditions.

5 Conclusion

This study provides a comprehensive assessment of the vertical compliance and rotational stiffness of different football surfaces using two test devices adopted by the FIFA QP. The findings reveal significant differences between natural, hybrid, and artificial turf systems. Artificial turf exhibited greater peak shock absorption, peak deformation, and energy return, while natural and hybrid turfs demonstrated higher resistive torque at 10 degrees of rotation. These insights contribute to a deeper understanding of player-surface-related measurements and have underpinned amendments to the FIFA QP to align performance characteristics across the range of playing surfaces currently used in football. These findings could contribute to future design and optimisation of football playing surfaces, by improving alignment in mechanical surface properties across natural, hybrid, and artificial systems.

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Data availability Data will be available from authors upon reasonable request.

Declarations

Conflict of interest Johsan Billingham as well as Professors Steph Forrester and Paul Fleming are members of the Editorial Board of the Sports Engineering journal and were blinded from the editorial process for this submission. The remaining authors have no conflicts of interest to declare.

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